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ORIGINAL PAPER

Phosphorus leaching through intact soil cores as influenced by type and duration of manure application

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Abstract Leaching of phosphorus (P) in manure-amended soils has received increased attention as a significant source of non-point source P pollution. Intact soil cores were collected from fields on a farm in Southern New York to test the effects of long-term dairy or poultry manure application on P leaching. Nine fields were selected (four poultry, four dairy, and one unamended) to represent a broad range of P saturation levels (5.3 to 62.4%) in the topsoil (0–7.5 cm). Water was applied weekly at a rate matching a 1-year return period storm for the study area (230 mm h^{-1}). Dissolved reactive P (DRP) losses in leachate from all soil cores ranged from 0.007 to 0.055 kg P ha^{-1}, except in two fields with long-term histories of dairy and poultry manure application, where losses averaged 0.21 and 0.45 kg P ha^{-1}, respectively. Hydrographs of the field with the dairy manure history suggested preferential flow as an explanation of leachate P enrichment. In the poultry manure amended field, high levels of soil P saturation throughout the profile suggested subsoil P desorption as a factor controlling leachate P. Surface application of dairy manure to the soil cores (167 kg total P ha^{-1}) increased the mean leachate DRP concentration from 1.5 to 10.5 fold. After five leaching events spanning 22 days, DRP concentrations remained 2.0 to 13.4 fold above pre-manure application levels. This study points to saturation of P in subsoils by long-term manure application as a key concern to P loss in leachate and highlights the role of annual manure additions on subsurface P loss potential.

Keywords Phosphorus leaching · Manure · Dairy · Poultry

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Introduction

Non-point source losses of phosphorus (P) are of environmental concern due to the role of P in accelerating fresh water eutrophication of surface waters (Carpenter et al. 1998). Agriculture has been implicated as a major contributor to those losses in the United States (USEPA 1996). Most research on P loss from agriculture has focused on gaining a better understanding of overland flow transport mechanisms (runoff and erosion), as opposed to subsurface flow. Until relatively recently, subsoil with its generally high P sorption capacity was thought to provide an adequate filter for P in subsurface flow (Gächter et al. 2004; Sims et al. 1998). However, a growing number of studies have revealed that P losses via subsurface flow can be high and can pose environmental risk when there is a lateral connection to surface waters through shallow groundwater or artificial drainage (Dils and Heathwaite 1999; Sims et al. 1998).

Leaching losses of P are usually highest when storm events follow recent manure or fertilizer applications (Barton et al. 2005; Geohring et al. 2001; Kleinman et al. 2005). For instance, Kleinman et al. (2005) found that dissolved reactive P (DRP) in leachate from intact soil cores was highest immediately following poultry manure application. Elsewhere, Geohring et al. (2001) documented a rapid initial peak in DRP concentration in effluent from tile drains in a field plot amended with liquid dairy manure. This peak was accentuated by wet soil conditions at the time of manure application that maximized water flux through the soil.

A variety of soil-related factors have been identified as key to enhancing P leaching potential in soils. The presence of pronounced preferential flow paths, commonly found in permanent grasslands or no-till cropping systems, allows P in leachate to by-pass areas of high sorption capacity in the subsoil (Butler and Coale 2005; Gächter et al. 1998; Stamm et al. 1998). Research by Dils and Heathwaite (1999) showed peak concentrations greater than 1 mg P L^{-1} from tile drains in high storm flow events. The authors linked these high P losses to extensive macropore flow combined with recent fertilizer application (Dils and Heathwaite 1999). Such peak flow concentrations can have significant impact on the receiving waters because there is little or no dilution effect if P is rapidly lost through preferential flow, contrary to what is commonly seen for runoff (McDowell and Sharpley 2002).

Preferential flow is of immediate environmental concern when linked laterally to surface waters, but it can also have long-term implications on leaching losses of P over time. Soils with long histories of fertilizer application above crop requirements can become saturated with P over depth through preferential flow or slow continuous high P matrix flow (Gächter et al. 2004). Phosphorus in subsoil was 1.2–2.5 times higher after 15 years of P fertilization and irrigation compared to unamended subsoil (Gächter et al. 2004). Butler and Coale (2005) found degree of P saturation (DPS) levels greater than 25% up to a depth of 60 cm after 4 years of dairy manure application suggesting a decreased ability of the subsoil to sorb P moving through the soil profile. This translocation of P to the subsoil from high P topsoil could equate to higher P leaching losses over time as the subsoil acts as a source of P through desorption into pore water (Gächter et al. 2004). Since subsoil P levels are rarely measured in agronomic settings, a clear understanding of their role in P leaching remains a priority.

In New York State (NY), recent strategies to minimize losses of P in overland flow, such as implementation of the NY P Runoff Index, limit P applications in fields that have a high or very high P risk of loss in overland flow (Czymmek et al. 2003). However, such strategies often ignore or downplay risks of sub-surface P losses. For instance, the current NY P Runoff Index allows applications in excess of P in crop removal on fields with a low or medium P Runoff Index score. The P Runoff Index does not include a P leaching factor, however, allowing for manure addition to a field even if leaching risks are high. Furthermore, such strategies will promote the build up of P in soils. In NY, 47% of the soils analyzed at the Cornell Nutrient Analysis Laboratory between 1995 and 2001 exceed the agronomic optimum (Ketterings et al. 2005). Better understanding of interactions between P in topsoil, manure management and P leaching potential in NY soils is needed to ensure current P management strategies do not exacerbate subsurface P losses.

The objectives of this study were to (i) quantify and characterize leaching losses of P from two NY soils with long term histories of either dairy or poultry manure amendments over time, and (ii) compare losses from the soil alone with leaching losses of P after recent surface application of dairy manure.

Materials and methods

Site description and field selection

Research was conducted on a farm in the Southern Tier of New York that has been using both liquid dairy and solid poultry layer manure as nutrient sources on their fields for up to 40 years. The farm was selected as a case study of the factors affecting P transport as it is representative of small NY dairy farms and had a wide range of soil management histories. Intact soil cores were taken in fields with soils classified as coarse-loamy, mixed, mesic Typic Fragiochrepts (Wellsboro channery silt loam) and loamy-skeletal, mixed, mesic Dystrochrepts (Oquaga channery silt loam). These soil series are well represented in the Glaciated Allegheny Plateau and Catskill Mountain Region (Major Land Resource Area 140), and part of the Northeastern Forage and Forest Region (Soil Conservation Service 1981).

Fields on the farm are subject to a 4 year corn (*Zea mays* L.) and 4 year alfalfa (*Medicago sativa* L.) rotation. Manure is typically surface applied in the fall (September–November), with subsequent shallow disk tillage (approximately 17.5 cm) in the spring (March–May) before planting. Mean annual precipitation for the area ranges from 890 mm to 1270 mm and monthly temperatures average –5°C to 17°C. Based on soil test P alone (i.e. without manure or P fertilizer addition), 51% of the fields on the farm rank high or very high on the NY P Runoff Index. Under concentrated animal feeding operation (CAFO) regulations (U.S. Department of Agriculture and U.S. Environmental Protection Agency 1999), manure and fertilizer application would only be allowed at P removal rates in ''high'' fields and no P applications would be allowed at all in ''very high'' fields (Czymmek et al. 2003).

Intact core collection and soil profile sampling

Nine fields were selected to represent (1) the three major categories of manure histories on the farm (4 poultry fields, 4 dairy fields and one unamended sod), and (2) a broad range in P saturation levels of the surface layer (0–5 cm). The selection was based on manure history of the fields as identified by soil P, copper and zinc levels (Brock et al. 2006a). Soil nutrient characterization and important hydrologic properties are shown in Tables 1 and 2, respectively. Three intact soil cores were obtained from each field within a 2 × 2 m square area in November, 2004. To collect the cores, 2.5 cm thick (Schedule 80) poly-vinyl chloride (PVC) pipe with an internal diameter of 30 cm and a length of 52 cm was pushed into the ground using a 2-Mg drop hammer (Kleinman et al. 2005). Compaction of the surface soil was avoided by leaving 2-cm of PVC pipe exposed, such that the intact core within the pipe had a depth of 50-cm. Following insertion of the pipe into the soil, the area around the core was excavated with a backhoe and the core was tipped to break contact with the subsoil. The core was then inverted, subsoil was evened off the bottom of the core, and depressions were backfilled with clean sand. The sand was covered with cheesecloth, held in place by a perforated PVC disk and a PVC cap (Fig. 1).

Soil profile samples were collected from each 2 × 2 m pit from which soil cores were extracted. Sampling occurred every 5 cm up to a depth of 20 cm and then every 10 cm up to a depth of 50 cm. Soils were dried in an oven at 40°C for at least 24 h and ground to pass a 2 mm sieve prior to laboratory analysis.

Cores were transported to a greenhouse facility in Ithaca, NY, where they were equipped with a drainage nipple and hose to direct free draining leachate to a collection container. The temperature of the greenhouse ranged from 21°C to 38°C over the duration of the leaching study. In the greenhouse, vegetation was removed from the surface of all the cores, such that each core surface consisted of bare soil only. Any existing biomass was clipped by hand and then sprayed with glyphosate 2 weeks prior to commencement of leaching to ensure no re-growth over the

Table 1 Field characterization including soil type, cropping systems, and topsoil (0–5 cm) characteristics for each of nine fields, mean (SE)

Field	N	Soil Type[a]	Crop (Rotation)	Topsoil (0–5 cm) sampled fall 2005 from pit			
				pH (in water) (1:1)	OM (%)	Mehlich-3 P (mg kg^{-1})	Mehlich-3 Ca (mg kg^{-1})
DM 1	2	Wellsboro	alfalfa (4 year corn/alfalfa)	6.5 (0.0)	7.3 (0.3)	219 (2)	2367 (233)
DM 2	2	Wellsboro	corn (4 year corn/alfalfa)	6.7 (0.1)	8.7 (0.5)	418 (14)	3353 (96)
DM 3	3	Oquaga	alfalfa (4 year corn/alfalfa)	6.3 (0.3)	7.7 (0.2)	274 (10)	2372 (90)
DM 4	2	Oquaga	corn (4 year corn/alfalfa)	6.4 (0.3)	5.6 (1.8)	454 (122)	2413 (499)
PM 1	3	Wellsboro	corn (4 year corn/alfalfa)	7.1 (0.1)	6.0 (0.1)	614 (49)	3484 (177)
PM 2	3	Wellsboro	corn (4 year corn/alfalfa)	7.0 (0.4)	5.2 (0.2)	651 (4)	4064 (247)
PM 3	3	Wellsboro	corn (4 year corn/alfalfa)	7.1 (0.0)	6.0 (0.5)	1104 (59)	5109 (552)
PM 4	2	Wellsboro	corn (continuous corn)	6.7 (0.2)	7.8 (0.3)	2440 (197)	10503 (160)
U	3	Wellsboro	grass (perennial sod)	5.4 (0.4)	7.6 (0.3)	64 (12)	1541 (169)

[a] Wellsboro soils are classified as coarse-loamy, mixed, mesic Typic Fragiochrepts. Oquaga soils are loamy-skeletal, mixed, mesic Dystrochrepts (Soil Survey Staff, NRCS 2005)

Table 2 Soil series classification for important water flow properties like hydrologic class, available water capacity, and permeability

Soil Series[a]	Hydrologic Class[b]	Available Water Capacity[b] (mm h^{-1})	Depth to Hard Pan[b] (m)	Permeability[b] (mm h^{-1})
Wellsboro	C	25-35	>1.5	152–508
Oquaga	C	20-43	0.5–1.0	152–508

[a] From NRCS USDA Soil Series Classification Database (Soil Survey Staff, NRCS 2005)

[b] From Soil Survey Steuben County, New York (United States Department of Agriculture Soil Conservation Service 1978)

duration of the experiment. Cores were covered with plastic to maintain soil moisture until the onset of the leaching experiment.

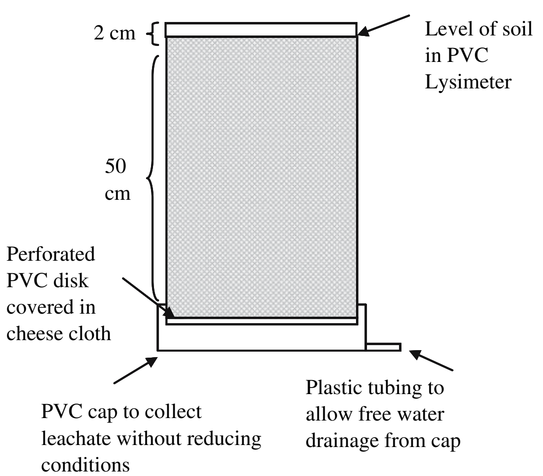

Fig. 1 Schematic of the intact soil cores used for the leaching experiment

Leaching of intact cores

Cores were brought to field capacity by applying 425 mm of deionized water to each core followed by free drainage for 48 h. Deionized water was applied at a rate of 230 mm h^{-1}, equating to a 1 h - 1 year return period storm for the study region in NY (1.65 L per event). Irrigation was conducted via a perforated plastic watering system placed 5 cm above the surface of the soil, with water applied in two batches separated by 5–7 h so as not to exceed the infiltration capacity of the soil. Water was applied every other day for a week and subsequently once a week for 133 days (Fig. 2). Leachate was collected 24 h after the second water application and immediately filtered through a 0.45 µm syringe filter and stored at 4°C until analysis. On day 139, liquid dairy manure was applied to the surface of each core with no incorporation at rates currently used at the case study farm to meet the N requirement of a corn silage crop, equivalent to a total P application

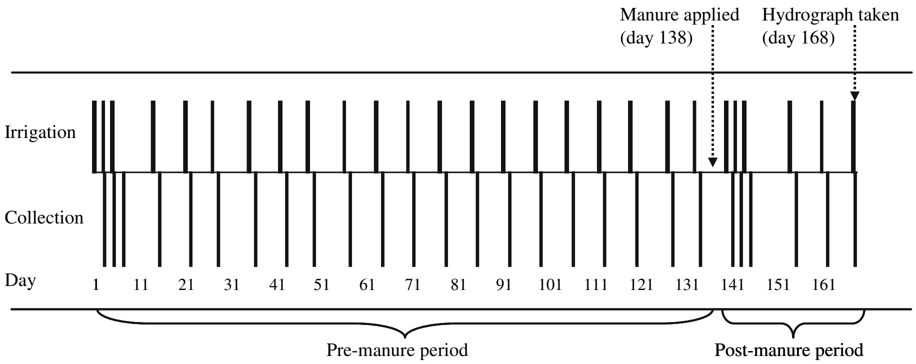

Fig. 2 Time line of events in leaching experiment

rate of 167 kg P ha^{-1} (149,600 L manure ha^{-1}). After manure application, water was applied 5 more times on days 140, 142, 144, 154 and 161 in the fashion described above.

On day 168 a final irrigation was conducted. However, to obtain hydrographs for each of the cores, leachate from this event was collected every 30 min for 30 h. Leachate volumes were plotted against time to assess core to core variability and to detect the presence of bypass or preferential flow. After completion of the leaching experiment, cores were destructively sampled over the same depths as was done at the time of collection. Soils were dried in an oven at 40°C and ground to pass a 2 mm sieve prior to analysis.

Chemical analyses

Leachate

Filtered leachate samples were analyzed within 48 h of collection for dissolved reactive P (DRP) using the stannous chloride method (Kuo 1996). Samples were analyzed for total dissolved P and Ca using a Spectro CIROS CCD ICP-AES (Spectro Analytical, Germany). The pH of the leachate samples was also measured.

Soils

Both field soil profiles and soil samples removed from cores after completion of the leaching experiment were analyzed for Mehlich-3 extractable P, Ca, Fe and Al by shaking soil with Mehlich-3 solution (1:5 soil to solution ratio) at 180 oscillations per min for 5 min (Mehlich 1984). Extracted P, Ca, Fe, and Al were detected with a TJA 61E ICP-AES (ThermoElectron Corporation, Waltham, MA). Soil pH was measured using a 1:1 (v:v) soil to water extraction ratio. Soil organic matter (OM) was estimated by loss-on-ignition (Rowell 1994). The degree of P saturation (DPS) over depth was determined as:

$$\mathrm{DPS} = (\text{Mehlich-3P})/(\text{P sorption capacity}) \qquad (1)$$

where Mehlich-3 P represents P that has been sorbed by the soil and the P sorption capacity (PSC) is estimated by the equation of Brock (2006b) derived specifically from soils found on the case study farm:

$$\mathrm{PSC} = 21 * (\text{Mehlich-3Ca}) + 119 * (\text{Mehlich} - 3\text{Al}) + 49 * (\text{Mehlich} - 3\text{Fe}) - 2980 \qquad (2)$$

Manure sampling and analysis

Manure characteristics are shown in Table 3. Both manure sources were sampled in spring 2005. Three composite samples were taken per source from holding facilities on the farm. Samples were analyzed according to recommended methods for manure analysis (Peters et al. 2003). Manure P, K, and Ca were extracted using nitric acid-perchloric acid digestion and solutions were analyzed using a TJA 61E ICP-AES (Thermo

Table 3 Dairy and poultry manure analysis (2005)

Manure source	n	pH [a]	DM g kg^{-1}	OM [b] g kg^{-1} DM	Total N g kg^{-1} DM	Organic N g kg^{-1} DM	P g kg^{-1} DM	K g kg^{-1} DM	Ca g kg^{-1} DM
Liquid dairy manure	3	8.11	134.5	16.1	37.2	13.5	8.3	26.8	24.8
Solid poultry manure	3	8.03	311.6	50.2	36.4	10.4	24.5	47.1	242.0

[a] Determined in a 1:1 (v/v) water extract

[b] Determined by loss on ignition (Rowell 1994)

Electron Corporation, Waltham, MA). Total N was analyzed by the combustion method adapted from AOAC 990.3 (Horwitz 2000) using a Vario Max CN combustion analyzer (Elementar Americas Inc., Mt. Laurel, NJ). Ammonium N was determined colorimetrically by USEPA method 351.2 (USEPA 1983) using a QuickChem Autoanalyzer (Lachat Instruments, Milwaukee, WI). Manure pH was measured in distilled water as a 1:2 (v:v) manure:water slurry.

Data analysis

Mean, flow weighted leachate P concentrations were calculated for events before and after manure application. Leaching data were analyzed as a repeated measures design using a random coefficient model with field, soil core replicate and time as random parameters using Statistical Analysis System for Windows, version 8 (Littell et al. 1996). Significant differences between soils and cumulative leaching losses were determined using ANOVA and least significant differences in S-PLUS version 6.2 (Insightful Corporation, Seattle, WA). An α of 0.05 was used to identify statistically significantly differences, unless otherwise noted.

Results and discussion

Soil chemical properties

Mehlich-3 P and Ca

The depth distribution for Mehlich-3 P and Mehlich-3 Ca followed the same general pattern for poultry and dairy manured soils, differing from trends observed in the unamended soil (Fig. 3E and F). Similar trends in P and Ca with depth in soils receiving poultry and dairy manures have been reported elsewhere (Kleinman et al. 2003; Butler and Coale 2005), reflecting the high concentrations of P and Ca in these manures (Table 3). Notably, surface soils receiving poultry manure were 1.4 to 5.4 times higher in Mehlich-3 P and 1.2 to 3.1 times higher in Mehlich-3 Ca than the dairy manured soils with the highest Mehlich-3 P and Ca. Differences in soils receiving long-term application of poultry and dairy manure likely reflect inherent differences in the manures themselves (e.g., Sharpley et al. 2004). For instance, based upon properties described in Table 3, application of poultry and dairy manures at identical N rates would result in three times more P and ten times more Ca in the poultry manure than in the dairy manure.

Differences in Mehlich-3 P and Ca between poultry and dairy manured soils were restricted to surface samples. With one notable exception, these differences disappeared at depths greater than 20 cm. In fact, at lower depths, Mehlich-3 P and Ca of the manured soils did not differ substantially from the unamended soil (Fig. 3E and F). The one exception was field PM4, which had elevated Mehlich-3 P and Mehlich-3 Ca to a depth of 50 cm. This field has been in continuous corn with annual applications of poultry manure for more than 40 year at rates to meet crop N requirements and represents an extreme case of P accumulation in the topsoil. Indeed, surface soil Mehlich-3 P levels of the PM4 sample (approximately 2400 mg P kg^{-1}) exceed any reported in the soil fertility literature to date.

pH, OM, Mehlich-3 Al and Fe

There were no systematic differences in pH, OM, and Mehlich-3 Fe and Mehlich-3 Al with depth in the soil profile between poultry and dairy manure

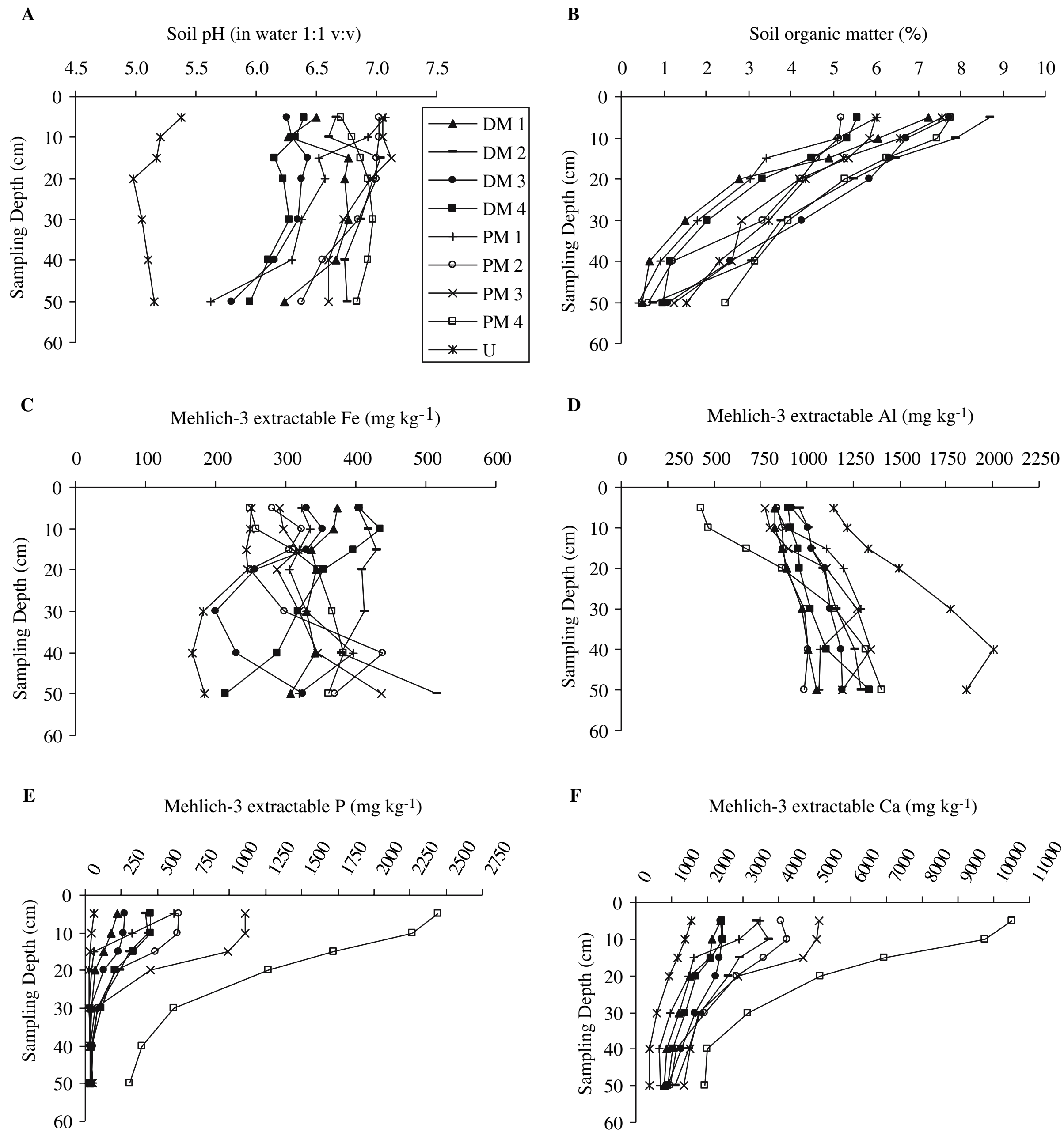

Fig. 3 Depth distribution of soil pH (A), organic matter (B), and Mehlich-3 extractable Fe (C), Al (D), P (E), and Ca (F) in four dairy manure amended soils (DM), four poultry manure amended soils (PM) and one unamended soil from a case study farm in the Southern Tier of New York (n = 4)

amended soils (Fig. 3A–D). However, the unamended soil had a significantly lower pH over depth than the manured fields (Fig. 3A). Dairy manure amended fields receive regular lime applications to maintain agronomic optimum pH levels and poultry layer manure acts as a liming material due to its high calcium carbonate equivalent (Sato et al. 2005). The unamended soil also had consistently higher Mehlich-3 Al levels than did the manured soils, likely due to lower pH (Fig. 3D). Mehlich-3 Al levels in the manured soils tended to increase with depth, reflecting the combination of liming and manure application history (Moore and Edwards 2005), as well as pedogenic processes. Soil organic matter levels in the topsoil (Fig. 3B) were high compared with other studies of NY manure amended soils (e.g., Galbraith et al. 2003; Ketterings et al. 2003) and may reflect the combination of a minimum tillage system and high manure application rates used on the case study farm.

Leachate trends prior to manure application

During the first week of the experiment when leaching events occurred every other day, flow volumes were high, ranging from 127 mm to 190 mm per event. The ratio of leachate flow to irrigation volume (LI ratio) as described by Kleinman et al. (2005) ranged from 0.54–0.81 during this time. Flow volumes dropped following the 10-day delay between irrigation events on day 5 and day 14 with LI ratios ranging from 0.25 to 0.42. Volumes stayed within this range on day 21 but subsequently increased to LI ratios ranging from 0.43 to 0.67 on day 27. Flow volumes fluctuated within this range for the remainder of the experiment, possibly due to fluctuating greenhouse temperatures over the course of the experiment.

For nearly all soil cores, no significant trends in leachate DRP concentrations or loads were observed over time. However, leachate DRP concentrations and loads increased over time from the two cores obtained from field PM4 (Fig. 4). The DRP concentrations and loads did not appear to fluctuate with flow volumes in any of the cores. Because of the lack of significant trends over time in all but the two cores, cumulative DRP losses were evaluated between cores for the entire leaching period prior to manure application.

Mean cumulative DRP losses ranged from 0.007 kg P ha^{-1} to 0.055 kg P ha^{-1} except for cores derived from fields DM4 and PM4 where mean DRP losses were 0.21 kg P ha^{-1} and 0.45 kg P ha^{-1}, respectively (Fig. 5B). However, due to the high variability between cores taken from field DM4, leachate DRP concentrations and losses from these cores were not statistically different from other fields. Mean flow-weighted concentrations of DRP in leachate before manure application were low in almost all cases, ranging from 0.003 mg P L^{-1} to 0.146 mg P L^{-1} (Fig. 5A). Only leachate from fields DM4 and PM4 had DRP concentrations higher than the 0.05–0.10 mg total P L^{-1} concentration cited as a threshold of concern for surface water eutrophication (USEPA 1996). Concentrations of DRP in single leaching events from field PM4 cores ranged from 0.6 mg L^{-1} to 10.3 mg L^{-1} while those from field DM4 cores ranged from 0.16 mg L^{-1} to 3.3 mg L^{-1}.

The variability in P loss from cores obtained from field DM4 and the elevated P losses seen from these cores may be explained in part by flow

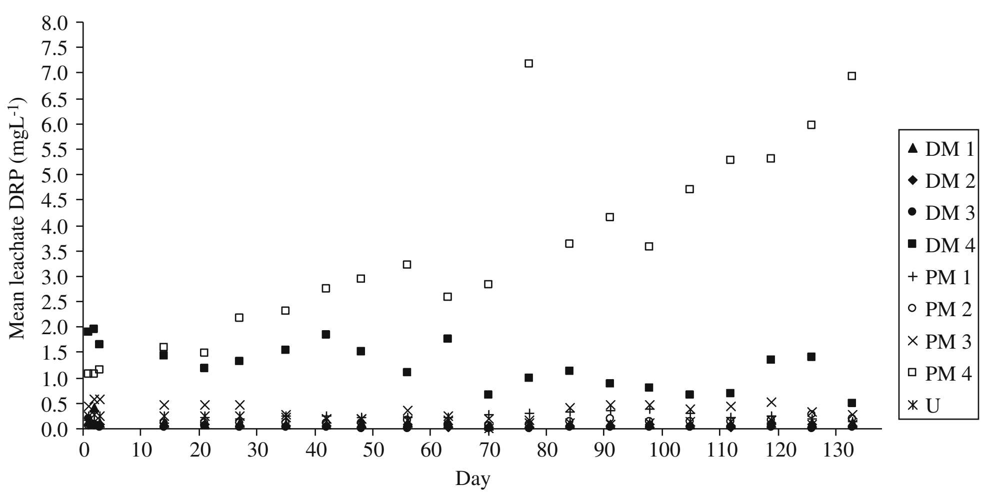

Fig. 4 Leachate dissolved reactive P over time averaged over cores (50 cm depth) for each time period

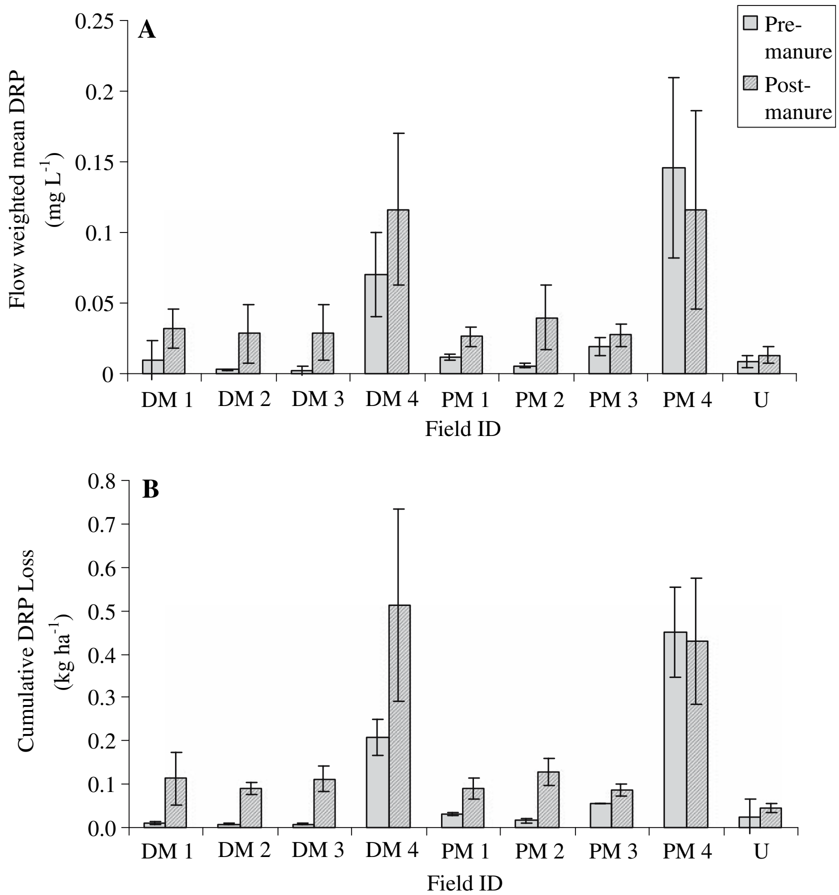

Fig. 5 Cumulative concentration(**A**) and loss (**B**) of dissolved reactive P (DRP) in leachate from soil cores (50-cm depth) before and after surface application of dairy manure. Amounts before manure application represent 22 leaching events spanning 133 days, whereas amounts after manure application represent 5 leaching events spanning 22 days

patterns. Figure 6A depicts the mean hydrograph, generated from all cores except for those obtained from fields PM4 and DM4. Immediately after the first application of irrigation water, leachate volume was low (time = 0–3 h). This period likely represented the gradual saturation of the core by surface-applied water that replaced water already in storage, causing it to leach. After the second water application (at 3 h), a steady release of leachate is seen until 10 h after the initial water application. Cores from field DM4 did not show this pattern of water movement (Fig. 6B). One of the cores from this field ponded on the surface with minimal percolation. As the hydrograph data were taken after manure applications had occurred, it is possible that there was some surface sealing of soil pores due to the manure as the core transmitted flow prior to manure addition. The other core from field DM4 showed an initial saturation period similar to other cores after the first water application. However, after the second irrigation batch, 61 mm of water drained in a single 30 min period. This indicates rapid preferential flow that could account for the high leachate P losses seen from this core.

The highest leachate losses from bare soil were measured from cores obtained from field PM4. As described above, soils within field PM4 possessed elevated DPS throughout the entire core depth of 50-cm (Fig. 7). Again, it is likely that long-term application of poultry manure at high rates and translocation of applied P through the soil profile produced the elevated DPS of the subsoil in this field. As DPS is strongly tied to P desorption (Sharpley and Rekolainen 1997), and DPS has been shown to be an effective indicator of P leaching potential (Maguire and Sims 2002), it is likely that the elevated losses of P from the PM4 cores were associated with the elevated DPS found throughout the soil profile.

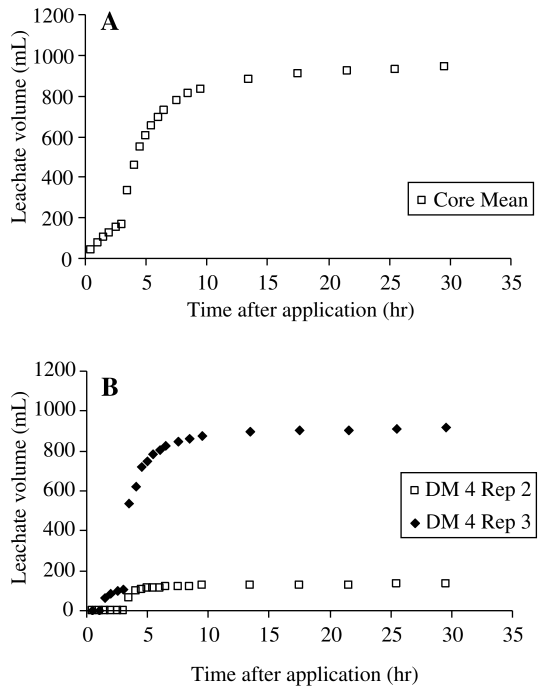

Fig. 6 Hydrograph with means of all cores excluding field DM4 and PM4 (**A**) compared to the hydrograph from field DM4 (**B**)

The role of DPS of surface soil in P leaching was less obvious than that suggested by previous studies. Cumulative leaching losses and mean, flow weighted leachate DRP concentrations were not correlated to surface soil 0.01 M $CaCl_2$-P, Morgan extractable P, or total P. Neither were they correlated with surface soil DPS or with DPS of any of the subsoil depths suggesting that if preferential flow is minimal, and the subsoils are not P saturated, the subsoil is capable of filtering P that is leached from the surface soil (Djodjic et al. 2004). These findings differ substantially from those of Heckrath et al. (1995), McDowell and Sharpley (2001), and Maguire and Sims (2002), who reported strong positive relationships between the P content of surface soils (measured as Olsen-P, Mehlich-3 P, 0.01 M $CaCl_2$-P and DPS) and dissolved P concentration in leachate. Soils in the current study represented a broad range of DPS and Mehlich-3 P levels, equal or greater to those observed in the other studies, and the range should be wide enough to lead to differences in leachate water quality as observed by the other studies. However, in the studies of McDowell and Sharpley (2001) and Maguire and Sims (2002), cores were shallow (~20 cm), representing leaching from the surface soil horizon only. It may be that the deeper cores used in the current study, which included subsurface horizons, complicated the relationship. In addition, recent additions of soluble P sources in those studies, designed to produce broad gradients in surface soil P content, may have contributed to the findings of those studies. Results from the current study call into question the ability to predict leachate P concentrations from surface layer soil test P data alone.

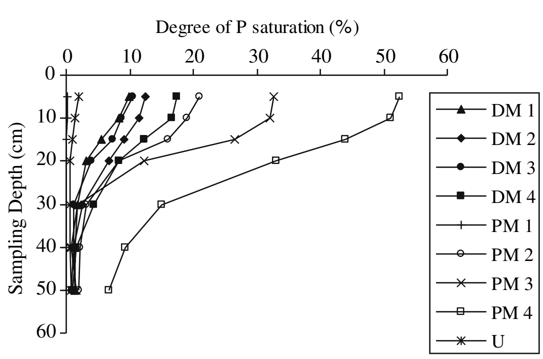

Fig. 7 Depth distribution of the degree of P saturation in soil cores from 9 fields differing in manure application history

Leachate trends after manure application

After manure application, mean cumulative DRP losses in leachate over 5 events ranged from 0.045 kg P ha^{-1} to 0.51 kg P ha^{-1} (Fig. 5), representing 1 to 15 times the amount of DRP leached over 22 events from soil without manure. Changes in leachate DRP losses paralleled changes in leachate DRP concentrations. After dairy manure application, mean flow weighted DRP concentrations ranged from 0.01 mg L^{-1} to 0.12 mg L^{-1}, approximately 1.5 to 10.5 times the concentrations observed prior to manure application. Similar trends following manure application have been documented elsewhere. Geohring et al. (2001) described rapid elevation in the DRP concentration of tile drain effluent after dairy manure applications in clay loam soils in situ. Likewise, Kleinman et al. (2005) observed

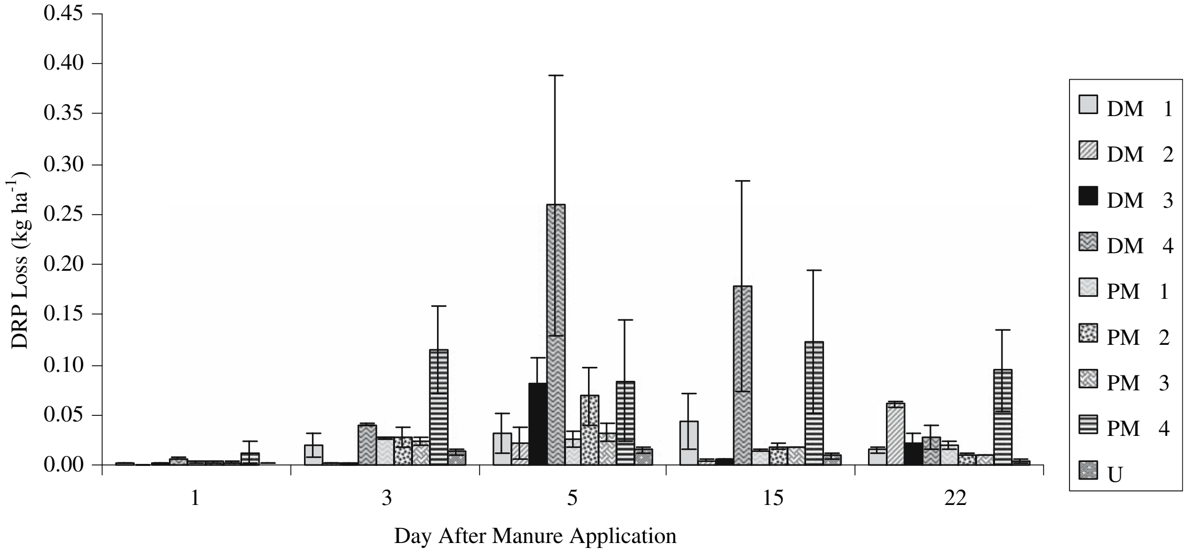

Fig. 8 Loss of dissolved reactive P in leachate following surface application of dairy manure over time from nine soil cores varying in manure history

significant increases in leachate DRP concentrations after poultry manure applications to intact soil cores.

One notable exception to the general trend of increasing leachate DRP loss and concentration with manure application occurred with cores obtained from field PM4. In those cores, DRP concentrations actually decreased after manure application. Leaching depths decreased by half in one replicate from this field after manure application, from an average of 99 mm per event before manure application to 31 mm per event after manure application. Such a decline in flow suggests that plugging of macropores with dairy manure solids affected leachate quality. Coincidentally, mean DRP concentrations declined from 0.2 mg L^{-1} before manure application to 0.02 mg L^{-1} after manure application.

In all fields, DRP losses after manure application represented less than 1% of P applied in dairy manure to the surface of the core. Barton et al. (2005) found total P concentrations in leachate after a single large dose of wastewater effluent in the field to represent between 1% and 16% of that applied depending upon the soil type. The lower proportion in P loss observed in the current study is likely due to the fact that only DRP was measured in leachate, whereas in the previously mentioned studies, total dissolved P in leachate was compared to P applications. Indeed, Kleinman et al. (2005) found a similar range of DRP losses after application of poultry manure to intact soil cores.

There was a significant quadratic time effect for P leaching losses after manure application (Fig. 8). For most intact soil cores, the highest losses of DRP in leachate occurred after the third leaching event (day 144), 5 days after manure application, with losses subsequently decreasing. Cores from field PM4 showed relatively constant losses of DRP in leachate from day 142 to 161. Kleinman et al. (2005) observed similar trends in leachate DRP from soil cores that showed both a delayed peak in DRP concentration after surface application of poultry manure and a gradual steady increase in DRP concentrations with time. Across all cores, however, DRP losses in leachate were still 2 to 27 times above pre-manure application levels by day 161. If soil water is moving through the cores via matrix or piston flow, it is possible the delay in DRP loss can be explained by the low leaching volume applied in each leaching event. At field capacity, approximately 707 mm of empty pore space existed in each of the soil cores therefore it would theoretically take 3 leaching events of 212 mm each for the first leaching event to exit the core. Gächter et al. (2004) found that DRP concentrations in agricultural drainage systems were highest after manure applications after the peak in discharge volume had occurred. They hypothesized that longer residence time of water in soil would lead to greater P desorption and thus higher P concentrations in the leachate. In other work, Gächter et al. (1998) showed that as soils become saturated, macropore flow is more affected by high concentrations of P in the topsoil. It is possible that the delayed peak in leachate P concentration is related to the longer residence time of the percolating water.

Conclusions

Phosphorus leaching losses from soil cores from farm fields with varying manure histories were minimal despite accumulation of P in the topsoil in fields with the longest manure application history. Leaching losses from intact soil cores were not related to soil P saturation levels at the surface or at different depths, with the exception of cores from one field representing extreme P accumulation. That field had received intensive applications of poultry manure and soil cores had elevated DPS levels throughout their profiles, resulting in substantially elevated P leaching losses.

Leaching losses were higher after surface application of dairy manure. A delay in the peak of P leaching loss over time following the manure addition could be explained by mass flow conditions in the cores. The greatest losses of P are likely to occur when severe rains or snow melt closely follow manure applications. Care should be taken to minimize these risks, especially in fields that are likely to contain preferential flow paths (perennial sods, or no-till cropping systems).

We conclude that implementation of best management practices to minimize runoff risks from this case study farm should be the primary focus for most fields as P leaching losses are low and implementation of the NY P Runoff Index will limit additional manure applications to the fields with the most elevated P saturation levels in the surface layer. Management strategies to mitigate P loss must be site specific as the transport mechanisms causing the greatest risk of P losses from soils with elevated P saturation levels are likely to be different on each field. However, care should be taken to avoid saturation of subsoil as losses of P in leachate may increase and it is uncertain how long it will take for cropping or leaching process to draw down subsoil P concentrations once they are elevated.

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